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An Updated Assessment of NASA Ultra-Efficient Engine Technologies

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ABSTRACT

NASA's Ultra Efficient Engine Technology (UEET) project features advanced aeropropulsion technologies that include highly loaded turbomachinery, an advanced low-NO_x combustor, high-temperature materials, and advanced fan containment technology. A probabilistic system assessment is performed to evaluate the impact of these technologies on aircraft CO_2 (or equivalent fuel burn) and NO_x reductions. A 300-passenger aircraft, with two 396-kN thrust (85,000-lb) engines is chosen for the study. The results show that a large subsonic aircraft equipped with the current UEET technology portfolio has very high probabilities of meeting the UEET minimum success criteria for CO_2 reduction (–12% from the baseline) and LTO (landing and takeoff) NO_x reductions (–65% relative to the 1996 International Civil Aviation Organization rule).

INTRODUCTION

Created in 2003, NASA's Vehicle Systems Program (VSP) streamlines vehicle systems research and development by consolidating several independent programs that focused on air-transportation technologies. It invests in vehicle technologies to protect the environment, makes air travel more accessible and affordable for Americans, enables exploration through new aerospace missions, and augments national security. The VSP is made up of seven core projects, which are:

- Quite Aircraft Technology (QAT)
- Ultra-Efficient Engine Technology (UEET)
- Efficient Aerodynamics Shapes and Integration (EASI)
- Integrated Tailored AeroStructures (ITAS)
- Autonomous Robust Avionics (AuRA)
- Low-Emission Alternative Power (LEAP)
- Flight and Systems Demonstration (F&SD)

This paper focuses on the assessment of Ultra-Efficient Engine Technologies (UEET).

Throughout the past century, propulsion innovations were the driving force behind the evolution of air transportation. Advances in propulsion system technology offer the greatest single contribution to the improvement of fuel economy, capacity, and the environmental impact of commercial aircraft. In the twenty-first century, propulsion will continue to be the enabling technology to revolutionize air transportation. As aviation grows, we must reduce aircraft noise and emissions as well as contaminants from airports. Improved environmental protection will be a vital element to ensure U.S. air transportation viability and global leadership.

The UEET project is designed to revolutionize the state of the art in turbine engine propulsion and propulsion/airframe integration technologies with specific objectives to reduce aircraft CO_2 (or equivalent fuel burn) and NO_x emissions relative to 1997 production engines. Currently, it features advanced technologies that include:

Tech ID	Technology Name
tech-1	Advanced low NO_x combustor
tech-2	Highly loaded compressor technology
tech-3	Highly loaded high-pressure turbine system
tech-4	Highly loaded low-pressure turbine system
tech-5	Ceramic matrix composite (CMC) turbine vane
tech-6	CMC combustor liner
tech-7	Low conductivity ceramic thermal barrier coating (TBC) for turbine airfoils
tech-8	Advanced turbine airfoil and disk alloys
tech-9	Advanced fan containment
tech-10	Active tip-clearance control technology

These technologies are described in Table 1.

The current (2004) results are compared with those from the 2003 assessment [1], and are used to provide guidance for the development of a robust UEET technology portfolio, and to prioritize the most promising technologies required to achieve UEET project goals for the CO_2 and NO_x reductions.

In 2004, the *active-tip clearance control technology* was book-kept under the Intelligent Propulsion System Foundation Technology (or Propulsion 21) project, which was to be the follow-on project of UEET. However, for the purpose of comparison with the 2003 results, it is included in the current assessment. Also, the 2003 propulsion-airframe integration technology, *high Reynolds number design tool* is no longer a UEET technology. It is considered a design tool and is

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Advanced low NOx combustor—a low NO_x emission combustor concept features lean burning concept.
Highly loaded compressor technology—technology that will enable higher compressor stage work factors. Lower system weight, improved overall performance will result in lower fuel burn and lower CO_2.
Highly-loaded high-pressure turbine (HPT) system—technology that will allow reduction in number of turbine stages and hence reduction part counts and cooling air requirements, which will result in CO_2 (or equivalent fuel burn) reduction.
Highly-loaded low-pressure turbine (LPT) system—technology covers development of LPT and aggressive transition duct. Both of these technologies use flow control technique and will reduce number of LP stages.
Ceramic matrix composite (CMC) turbine vane—CMC that will allow HPT vanes to operate at significantly higher turbine inlet temperature (hence reduce the cooling), which will result in CO_2 reduction.
CMC combustor liner—CMC technology that will allow combustor liners to operate at higher liner temperatures, which will result in NO_x reductions.
Low conductivity ceramic thermal barrier coating (TBC) for turbine airfoils—TBC that will allow turbine airfoils to operate at significantly higher temperatures, which will result in CO_2 reduction.
Advanced turbine airfoil and disk alloys— (1) light-weight single crystal super-alloy with improved temperature capability that will allow turbine blades and vanes to operate at higher operating temperatures, which will result in CO_2 reduction. (2) dual microstructure nickel base super-alloy turbine disks which can be tailored to optimize the disk behavior in high-temperature environment.
Advanced fan containment—material/structural concepts for improved (lighter) weight, impact damage tolerance, and noise-reducing fan containment case.
Active tip-clearance control technology—actively-controlled fan, compressor, and turbine to reduce fan, compressor, and turbine tip clearances, which will improve the component efficiencies and result in CO_2 reduction.

Table 1: Description of 2004 UEET Technologies

descoped from the current assessment. And the *advanced compressor disk alloy* technology, also a 2003 technology, has been transferred to the industry. However, its benefits are included in the current assessment.

The UEET project goals are a 70% reduction (with a minimum-success criterion of 65% reduction) in LTO NO_x relative to the 1996 International Civil Aviation Organization (ICAO) standard and a 15% CO_2 reduction (with a minimum-success criterion of 12% reduction) relative to the current state of the art large subsonic transports.

A probabilistic system assessment is performed to evaluate the impact of these technologies on aircraft CO_2 (or equivalent fuel-burn) and LTO NO_x reductions. The statistical approach quantifies the uncertainties inherent in these new propulsion technologies and their influence on the likely outcomes of engine performance. Consequently, it provides additional insight into the risks associated with new technologies, which are often needed by the decision-makers to determine the benefit and return-on-investment of new propulsion technologies.

ANALYSIS APPROACH AND PROCEDURES

Expert Opinion Elicitation

Expert opinions are an appropriate means of decision support when the scientific research contains few high-quality scientific studies and a valid research synthesis cannot be conducted—a situation that often occurs during the early or 'emerging' phase of a technology. Expert judgment must be used to judge the risks of emerging technology.

A technology audit scheme (TAS) developed by Kirby and Mavris [2] is used to elicit opinions from the NASA technologists identified as the focal point for each of the UEET technologies. It is based on the Delphi method [3], which is a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires and interviews interspersed with controlled opinion feedback. The focus of the TAS is to identify the applicable set of UEET technologies for the vehicle of interest, gather the required information, and compile the data necessary for the system analysis. The process is described in detail in Ref. [4].

The Beta Distribution

Based on the information obtained from the technologists, the 3-point estimates (maximum, minimum, and most-likely values) of the impacts (positive and/or negative) for each of the technologies are quantified. They are summarized in Table 2. A four-parameter beta distribution is then created for each of the technologies. The probability density function (PDF) of the beta distribution is:

$$f(x) = \frac{1}{B(p,q)} \frac{(x-a)^{p-1}(b-x)^{q-1}}{(b-a)^{p+q-1}} \qquad (1)$$

Technology Identification	Technology	Baseline values	Maximum impact	Minimum impact	Most-likely impact	Mean Impact	Standard Deviation	Distribution
tech-1	Advanced low NO_x combustor	AST correlation	75% LTO NOx reduction correlation	70% LTO NOx reduction correlation	72% LTO NOx reduction correlation	70% LTO NOx reduction correlation	1.67%	Beta
tech-2	Highly-loaded compressor	0.2745 HPC work factor; 0.9066 HPC poly eff.	+45% HPC work factor –0.16 pt HPC poly. eff.	+27% HPC work factor –1.16 pts HPC poly. eff.	+38% HPC work factor –1.66 pts HPC poly. eff.	+37.4% HPC work factor –1.06 pt. poly. eff.	3.16% 0.27 pt.	Beta
tech-3*	Highly-loaded HP turbine	0.848 loading; 0.92 adia. eff.	+21% HPT loading +0.5 pt. adia. eff.	+19% HPT loading –0.5 pts. adia. eff.	+20% HPT loading	+20% HPT loading +0.0 pt. adia. eff.	0.33% 0.17 pt.	Beta
tech-4*	Highly-loaded LP turbine	1.25 loading; 0.93 adia. eff. 0% bleed	+30% LPT loading +3 pts. LPT adia. eff. +0.5% HPC bleed	+25% LPT loading +1.0 pt. adia. eff. +2.0% HPC bleed	+28% LPT loading +2 pts. adia. eff. +0.5% HPC bleed	+27.9% LPT loading +2 pts. adia. eff. +0.8% HPC bleed	0.87% 0.33 pt. 0.24%	Beta
tech-5	CMC turbine vane	1366 K (2460 °R) vane temp. Nickel-based alloy 1st stage vane	+389 K (700 °R) HPT vane temp. CMC 1st stage HPT vane	+361 K (650 °R) HPT vane temp. CMC 1st stage HPT vane	+389 K (700 °R) HPT vane temp. CMC 1st stage HPT vane	+383 K (690 °R) HPT vane temp. CMC 1st stage HPT vane	4.6 K (8.3 °R)	Beta
tech-6	CMC combustor liner	15% cooling flow	reduce cooling flow by 60%	reduce cooling flow by 53%	reduce cooling flow by 57%	reduce cooling flow by 57%	1.21%	Beta
tech-7	Low conductivity thermal barrier coating (TBC) for turbine airfoil	1366 K (2460 °R) 1st stage HPT vane temp.; 1329 K (2360 °R) rest of the HPT and LPT blades and vanes temp.	+167 K (300 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	+83 K (150 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	+111 K (200 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	+111 K (200 °R) HPT & LPT blade and vane temp. (reduce cooling flow)	14.8 K (26.6 °R)	Beta
tech-8a*	Advanced turbine airfoil and disk alloys	HPT blades and vanes temp. same as above; Hi-temp nickel-base alloy HPT blades and vanes	+56 K (100 °R) HPT blade and vane temp. (reduce cooling flow); –3.85% HPT blade & vane densities	+28 K (50 °R) HPT blade and vane temp. (reduce cooling flow)	+43 K (78 °R) HPT blade and vane temp. (reduce cooling flow) –2.24% HPT blade & vane densities	+43 K (77 °R) HPT blade and vane temp. (reduce cooling flow) –2.15% HPT blade & vane densities	4.8 K (8.6 °R) 0.67%	Beta
tech-8b*	Advanced turbine airfoil and disk alloys	LPT blades and vanes temp. same as above; Hi-temp nickel-base alloy LPT blades and vanes	+57 K (102 °R) LPT blade and vane temp. (reduce cooling flow); –4.15% LPT blade and vane densities	+44.4 K (80 °R) LPT blade and vane temp. (reduce cooling flow) –0.32% LPT blade and vane densities	+52 K (94 °R) LPT blade and vane temp. (reduce cooling flow); –2.56% LPT blade and vane densities	+52 K (93 °R) LPT blade and vane temp. (reduce cooling flow); –2.47% LPT blade and vane densities	2.2 K (4.0 °R) 0.67%	Beta
tech-9*	Advanced fan containment	2768 kg/m^3 (0.1 lbs/in^3) case material density	–50% fan case weight	–10% fan case weight	–25% fan case weight	–27% fan case weight	–7%	Beta
tech-10	Active tip-clearance control technology	0.8961 fan poly. eff. 0.9066 HPC poly. eff. 0.9200 HPT adia. eff. 0.9300 LPT adia. eff.	+2.0 pt. fan poly. eff. +1.5 pt. HPC poly eff. +2.0 pt. HPT adia. eff. +0.75 pt. LPT adia. eff. +27 kg (+60 lbs) eng. wt.	+1.0 pt. fan poly. eff. +0.5 pt. HPC poly. eff. +1.0 pt. HPT adia. eff. +0.25 pt. LPT adia. eff. +9 kg (+20 lbs) eng. wt.	+1.5 pt. fan poly eff. +1.0 pt. HPC poly. eff. +1.5 pt. HPT adia. eff. +0.50 pt. LPT adia. eff. +18 kg (+40 lbs) eng. wt.	+1.5 pt. fan poly eff. +1.0 pt. HPC poly. eff. +1.5 pt. HPT adia. eff. +0.5 pt. LPT adia. eff. +18 kg (+40 lbs) eng. wt.	+0.17 pt. +0.17 pt. +0.17 pt. +0.08 pt. 3 kg (6.7 lbs)	Beta

*Note: results of tech 8a and 8b are combined to show the benefit of advanced turbine airfoil and disk alloys technology

Table 2: UEET Technologies and Their Uncertainties for a Large Subsonic Transport (based on 2004 Technology Audit)

and the cumulative density function (CDF) is:

$$CDF(t) = \frac{1}{B(p,q)} \int_0^t t^{\,p-1}(1-t)^{q-1}\, dt \qquad (2)$$

with the transformation: $t = \dfrac{(x-a)}{(b-a)}$

where the parameters a and b are the minimum and maximum values of the variable x, respectively; p and q are the distribution shape parameters and B is the beta function defined by:

$$B(p,q) = \frac{\Gamma(p)\cdot\Gamma(q)}{\Gamma(p+q)} = \int_0^1 t^{\,p-1}(1-t)^{q-1} dt \qquad (3)$$

The shape parameters p and q depend on whether the mode (most-likely value) is to the left or right of the midrange. They are determined using the method described in [5]. The resulted mean and standard deviation of the impact for each of the technologies are also summarized in Table 2.

The CDFs (Eq. (2)) are calculated numerically. All three equations are implemented into the Fast Probability Integration (FPI) computer code [6], and are used to perform the probabilistic system analysis of the UEET technologies.

System Analysis

The approach taken in this effort is to combine thermodynamic cycle analysis using NPSS (Numerical Propulsion System Simulator) [7], engine weight estimation using WATE (Weight Analysis of Gas Turbine Engines) [8], aircraft mission sizing using FLOPS (Flight Optimization System) [9], and FPI. A schematic of the integrated approached is shown in Fig. 1.

The computer code NPSS is used to calculate engine thrust, specific fuel consumption and LTO NO_x emissions. The engine weight is calculated by the WATE code. The results from NPSS and WATE are used by FLOPS for performing airplane mission and sizing analyses, and ultimately calculate the fuel-burn (or equivalent CO_2 emission) based on a 5556-km (3000 nautical miles) economic mission.

Probabilistic Analysis

All probabilistic analysis methods are approximate. Monte Carlo simulation, which is oftentimes referred to as the “exact” solution, is actually an approximate because a finite number of samples are always used. Thus, the nature of the approximation is one of “lack of data,” which can be reduced by increasing the number of samples. However, for large-scale high fidelity problems, the inefficiency of Monte Carlo simulation renders it impractical for use. Many efficient methods have been developed to alleviate the need for Monte Carlo simulation. These methods include the first and second-order reliability method (FORM and SORM) [10], the advanced mean value family of methods (AMV) (11], and the response surface method (RSM) [12]. These methods replace the original deterministic model with a computationally efficient analytical model in order to speed up the analysis.

For the current assessment, an advanced first-order reliability method is used. This method, based on the most-probable-point (MPP) concept, is one of the several methods in the FPI code. The code was developed under contract with NASA Glenn Research Center [13]. The role of FPI is to perform probabilistic analysis utilizing the results generated by NPSS, WATE, and FLOPS. The results are generated in the form of cumulative distribution functions (CDFs).

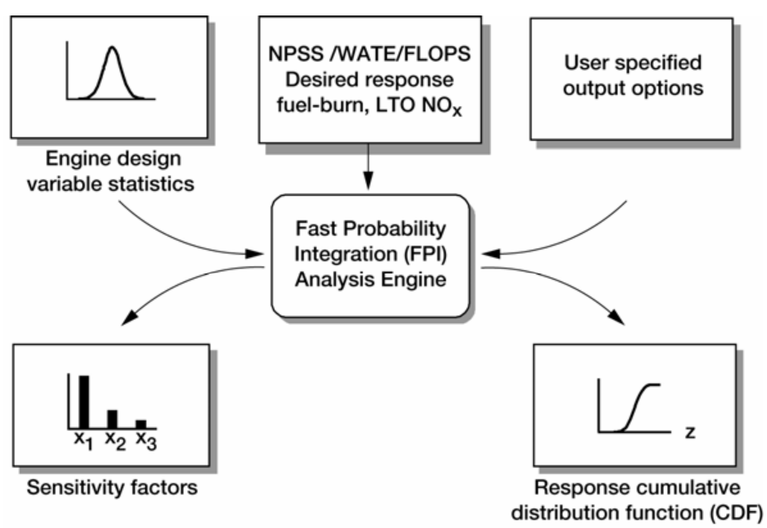

Fig. 1: Fast probability integration input/output schematic.

In addition, FPI is used to perform sensitivity analyses to rank the technologies in order of their impact on engine CO_2 and LTO NO_x emissions. Sensitivity values could be + or – in nature. For the current assessment, a positive value indicates that an increase in technology performance will have a positive impact on CO_2 (or LTO NO_x) reduction and a negative value has the opposite effect. Technology with the highest absolute sensitivity value is defined to be the most influential technology. The technology with the second highest absolute sensitivity value is the second most influential technology and so on. This approach ranks the technology in the order of their influence on engine performance (i.e., CO_2 or LTO NO_x reductions). The sensitivity information thus obtained from FPI is very useful from the design point of view. For example, engine performance reliability can be improved when uncertainties in the most influential technologies are reduced. Those technologies that do not have significant influences deterministically could nevertheless have strong influences on engine performance reliability if these technologies have huge uncertainties. Weak technology with large uncertainties may have probabilistic sensitivity factors more important than strong technologies with small uncertainties. Unlike deterministic analysis, sensitivity factors in probabilistic analysis are functions of both the deterministic sensitivity and the uncertainty (characterized by the standard deviation).

NOx Emission Index (EI) Correlation

The EI correlation used for the current LTO NO_x calculation is based on combustor sector test [14] and is defined as:

$$K(P_{t3})^{0.35}\exp[(T_{t3})/(300)] \times (FAR/delphi)^{c} \quad (4)$$

where:

K = technology constant
P_{t3} = combustor inlet total pressure
T_{t3} = combustor inlet total temperature, °F
FAR = fuel air ratio
delphi = 1 – fraction of combustor inlet air used for liner cooling
c = fuel injector design constant

RESULTS AND DISCUSSION

It is critical to assess the reliability of a new propulsion system because of inherent uncertainties in the UEET technologies. The current assessment focuses on the technical aspect of engine performance, i.e. mission fuel-burn and LTO NO_x emissions. The results are presented in the form of cumulative distribution functions (CDFs) and probabilistic sensitivities. A CDF gives a relation between a value up to certain magnitude of a response variable (fuel-burn or LTO NOx emissions) and the probability of its occurrence. The results are relative to those of the current state-of-the-art 300-passenger airplane (baseline).

The results show that, a large subsonic transport equipped with the current portfolio of UEET technologies has very high probabilities of meeting the minimum-success criteria of UEET project goals for both the CO_2 and LTO NO_x emissions exceed 83 and 99%, respectively. However, the project goal of –70% can be met with only a 62% confidence, a decrease from the 99% confidence obtained in 2003 assessment. The CO_2 reduction goal (–15%) cannot be met al all, a big decrease from the 97% confidence obtained in year 2003 assessment. The decrease is mainly due to the descoping of *propulsion-airframe integration technology* from the current assessment, and the penalty in component efficiency given to the *highly loaded compressor technology* by the technology experts. In year 2003 assessment, this technology was given an efficiency benefit. The results are shown in Figs. 2 and 3.

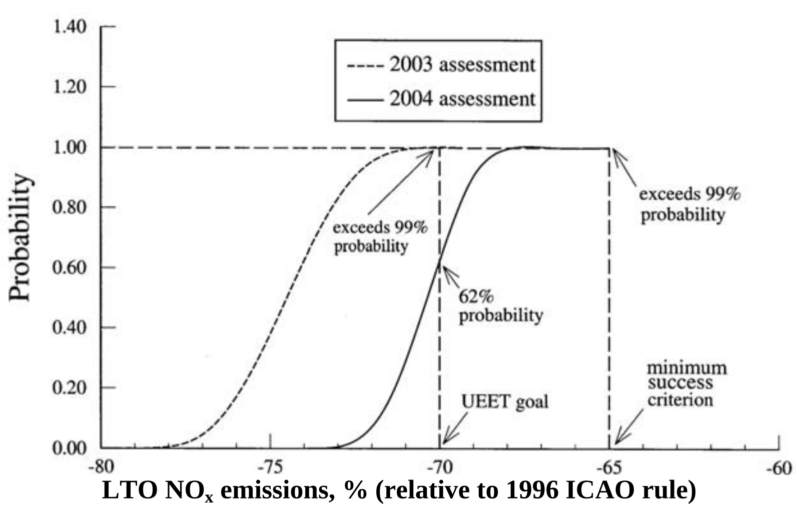

Fig. 2: Cumulative distribution function (CDF) of engine landing and take-off (LTO) NO_x emission.

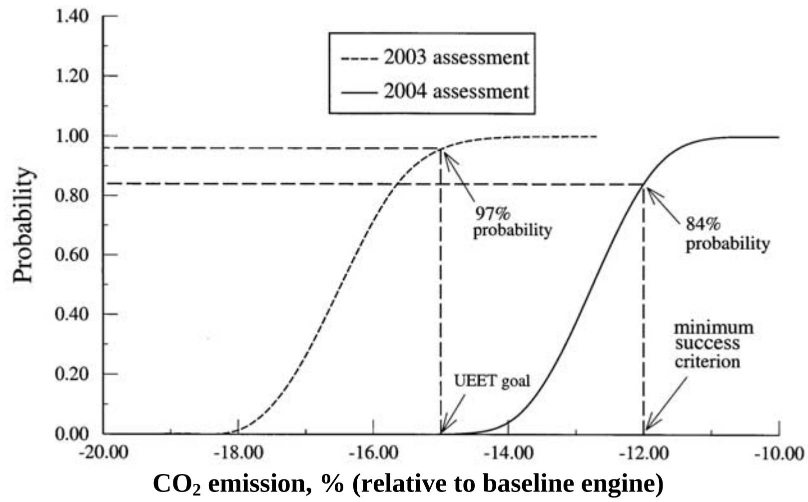

Fig. 3: Cumulative distribution function (CDF) of engine CO_2 emission.

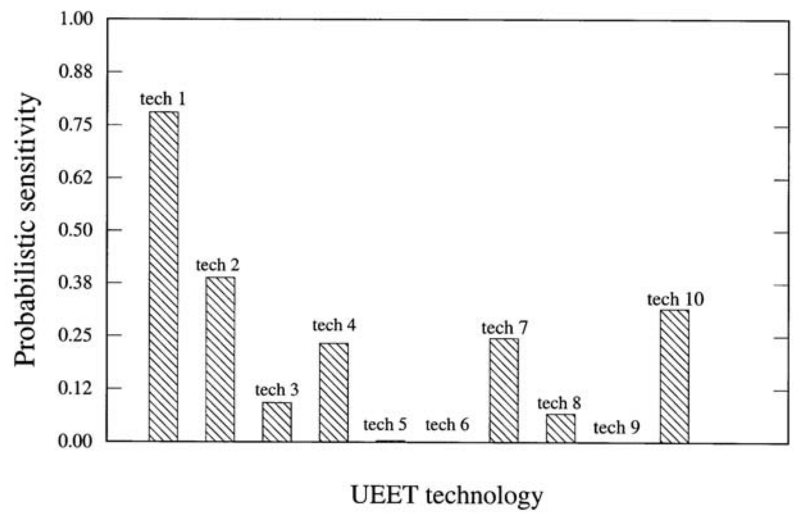

Fig. 4: Sensitivity of engine landing and take-off (LTO) NO_x emissions

LTO NO_x Emissions Sensitivity

The sensitivity of LTO NO_x emissions to the ten technologies, at 99% probability level is shown in Fig. 4. As expected, it shows that the *advanced low-NO_x combustor* (tech-1) has the dominant impact on the LTO NO_x emissions. It implies that to reduce the LTO NO_x emissions to meet the UEET goal, the biggest payoff is to focus on the combustor technology. The technologies tech-2 (*highly loaded compressor technology*), tech-4 (*highly loaded low-pressure turbine system*), tech-7 (*low conductivity ceramic TBC for turbine airfoils*), and tech-10 (*active tip-clearance control technology*) have moderate impact on the LTO NO_x emissions. These four technologies reduce the SFC (specific fuel consumption) significantly and thus have positive impact on the LTO NO_x emissions. Other technologies have minimal or no impact on the LTO NO_x emissions.

CO_2 Emission Sensitivity

For the CO_2 reduction, the sensitivity result at 99% is shown in Fig. 5. It shows that the *highly loaded low-pressure turbine system* (tech-4), *highly loaded compressor technology* (tech-2), *active tip-clearance control technology (tech-10)*, and the *low conductivity TBC for turbine airfoils* (tech-7) are the four most influential technologies. The influences of *highly loaded high-pressure turbine system* (tech-3), and *advanced turbine airfoil and disk alloys* (tech-8) are moderate. Other technologies have minimal or no impact on the fuel-burn reduction. These six top-ranking technologies are essentially the same top-six technologies from the 2003 assessment.

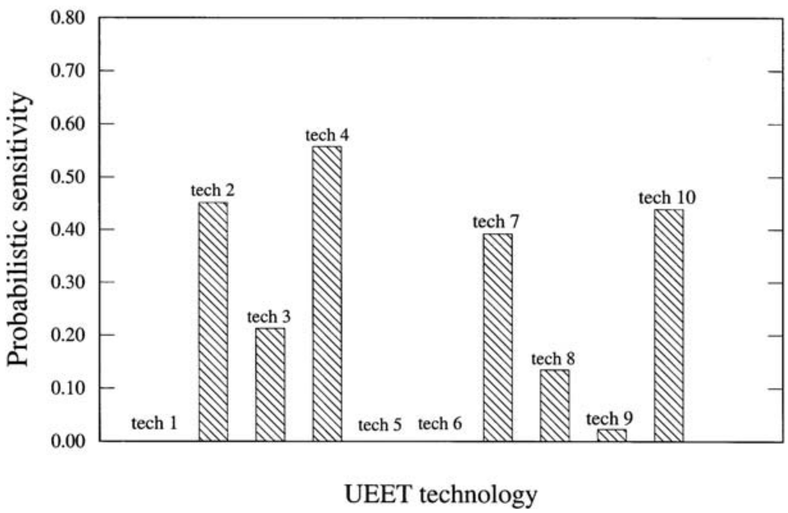

Fig. 5: Sensitivity of engine CO_2 emission

Among these six top-ranking technologies, tech-7 and tech-8 are material technologies. It is noted that tech-7 and tech-8 provide the same type of benefit, enable the amount of turbine cooling to be reduced. However, according to the expert opinion (see Table 1), tech-7 enables more cooling flow reduction. As a result, tech-7 has a much bigger positive impact on the CO_2 (or equivalent fuel burn) reduction. Another coolant-reduction technology, tech-5 (*1482 °C CMC turbine vane*), has insignificant impact on the CO_2 reduction, relative to tech-7 and tech-8. This is because tech-5's coolant reduction comes primarily from the first turbine vane (i.e., non-chargeable cooling) which is not as advantageous as a reduction in chargeable cooling (as for tech-7 and tech-8). Overall, the current results show that advanced materials are the key enablers for meeting the UEET project goals.

It is noted that, in a recent independent review of NASA's Aeronautics Technology Programs performed by the National Research Council, these six technologies have been rated either world-class or exceptionally good technologies [15].

CONCLUSIONS

Based on the current assessment results, the following conclusions are made:

(1) A large subsonic aircraft equipped with the UEET technologies has very high probabilities of meeting the minimum-success criteria of UEET project goals for CO_2 and LTO NO_x reductions, exceed 83 and 99%, respectively.

(2) The top-six UEET technologies for CO_2 (or equivalent fuel-burn) reduction are essentially the same top-six technologies from the 2003 assessment. They are:
   a. Highly loaded low-pressure turbine system
   b. Highly loaded compressor technology
   c. Active tip-clearance control technology
   d. Low conductivity ceramic thermal barrier coating for turbine airfoils
   e. Highly loaded high-pressure turbine system
   f. Advanced turbine airfoil and disk alloys

(3) The *Advanced low NO_x combustor* technology has the most and dominant impact on the LTO NO_x reductions.

(4) A technology that enables significant non-chargeable coolant reduction (such as *1482 °C CMC turbine vane*) is not as advantageous as those that enable significant chargeable coolant reduction (such as *Low thermal conductivity ceramic TBC for turbine airfoils* and *Advanced turbine airfoil and disk alloys*), for CO_2 (or equivalent fuel burn) reduction.

(5) Advanced materials are key enablers for meeting the UEET project goals.

(6) An effective expert opinion elicitation process, or technology audit, is crucial for performing technology assessment. A process that includes both the experts from NASA and the engine industry will ensure the audited data are indeed reasonable representation of each of the technologies' potential.

(7) The probabilistic approach provides a more realistic and systematic way to assess advanced propulsion technologies, because it accounts for their inherent uncertainties.

RECOMMENDATIONS

The development of the top-ranking UEET technologies should continue. With anticipated growth in air traffic, there is increasing concern over local air quality, climate change and health effects of emissions.

Certain regions of the world already have adopted policies that limit aviation growth to protect the environment. Without a doubt, emissions at the Nation's largest airports would limit capacity if they are not aggressively addressed. Improved environmental protection will be a vital element to ensure U.S. air transportation viability and global leadership. The development of these technologies complements well several projects in NASA's *Airspace Systems Program* (ASP).

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